Large Eddy Simulation of Sediment Transport in the Presence of Surface Gravity Waves, Currents and Complex Bedforms

Robert L. Street
Department of Civil and Environmental Engineering
Stanford University
Stanford, CA 94305
Phone: (650)723-4969 Fax: (650)725-9720 email: street@ce.stanford.edu

Award # N00014-00-1-0440
http://www-ce.stanford.edu:80/~street/

LONG TERM GOALS

Our long term goal is to develop numerical simulation techniques for generating accurate predictions of sediment transport in the coastal zone.

OBJECTIVES

Our current work aims to validate our numerical model of sediment transport in three dimensions and time and to demonstrate its usefulness for simulating time-dependent sediment transport phenomena. This will be accomplished by simulating various field experiments of sediment transport in the coastal zone, comparing results, and calibrating the model where necessary. Our tool is a Large Eddy Simulation [LES] that has recently been extended to handle high Reynolds number flows on the scale of meters.

The second phase of this work, to begin in the next fiscal year, will be to implement the above turbulence models and boundary conditions in a code to study the burial/unburial of cobbles/mines in the nearshore environment. This work will involve collaboration with Prof. J. Fernando at Arizona State University.

APPROACH

The LES code employed in this study solves the volume-filtered Navier Stokes equations for the velocity field and a volume-filtered advection diffusion equation with a settling term for the sediment

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concentration. The subfilter scale terms that arise from the volume filtering are represented by Zang's dynamic mixed model (1993). These equations are solved on a non-orthogonal, boundary following computational grid in three dimensions and time. The code is discretized in time with a semi-implicit method and in space with second order differencing. The discretized equations are solved with a fractional step/projection method.

All simulations performed at laboratory scales employed the version of the code used by Calhoun and Street (2001), but modifications to the code have been made for field scale simulations. In field scale simulations, the first grid point is no longer located in the viscous sublayer so that its effects on the fully turbulent outer flow must be parameterized. In this vein, a log boundary condition for the velocity field has been implemented and the eddy viscosity and eddy diffusivity in the near-bed layer have been augmented.

This modified version of the code will be used to simulate field experiments. This may involve slight adjustments to the augmented near-bottom eddy viscosity and diffusivity, and, possibly, to the sediment pickup function.

WORK COMPLETED

Two major tasks have been completed. First, the code has been extended to operate at field scales. A log boundary condition has been implemented for the velocity and the sediment boundary condition has been modified accordingly. The eddy viscosity and diffusivity have both been augmented in the near bottom region where the turbulence models do not account for all of the dissipation which occurs there. Second, sediment transport over a prototypical ripple that would form under a 10 second, 1 m high wave in 3 m depth of water has been simulated and the results analyzed for comparison with sediment transport trends reported in the literature (Katopodi et al., 1994, Hansen et al 1994, Scandura et al, 2000).

RESULTS

The LES code was used to simulate the sediment transport that results under a 10 second wave over sinusoidal-shaped ripples (uniform in the spanwise direction) with a wavelength of 2.25 m and amplitude of 0.1125 m (Figure 2b). This was accomplished by using an oscillatory pressure gradient in a channel flow because the actual free surface effects were expected to be small; free-surface effects will be included in the second phase of the work beginning in FY2002 as noted above. Present results were initialized with a forward going flow of about 0.6 m/s and a Rouse profile for the sediment

concentration. The sediment concentration field quickly becomes independent of its initial conditions, and attains periodic behavior after a single oscillation period. The oscillatory flow, however, is more strongly dependent on initial conditions. Although the flow is periodic in nature after one oscillation period, the flow is asymmetric, alternating between a flow similar in magnitude to the initial flow (~0.6 m/s) in the forward phase and a stronger reverse flow (~ -1.2 m/s). Vortex shedding is observed during the reverse flow phase and is the major entrainment mechanism for sediment in the flow.

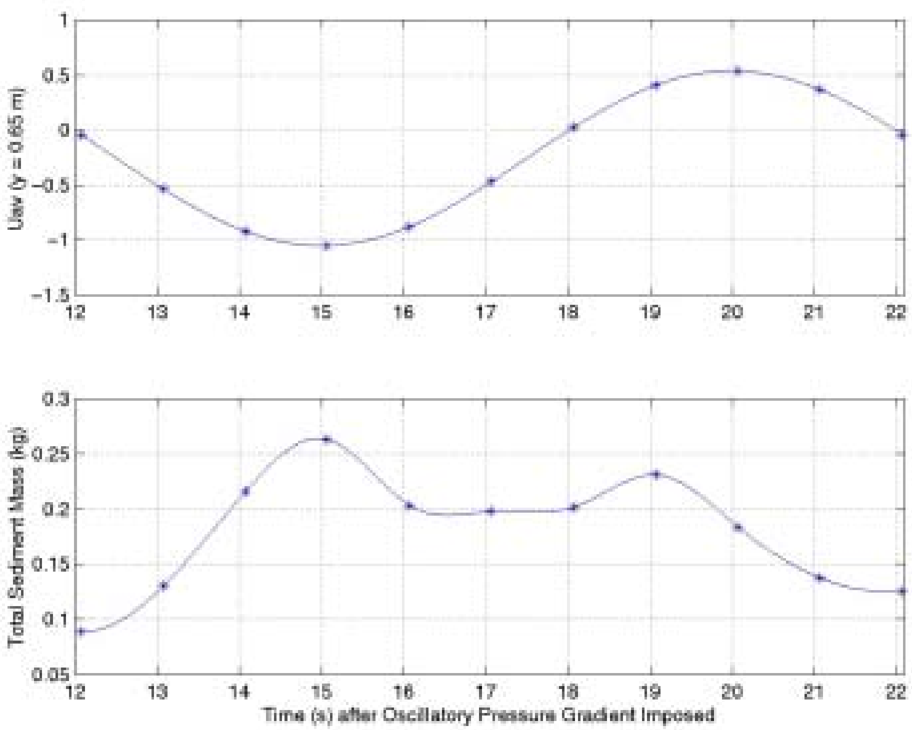
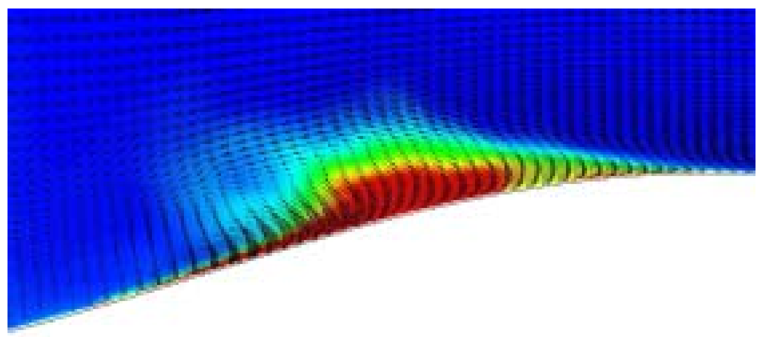


Figure 1. Total Sediment Mass in Domain vs. Time

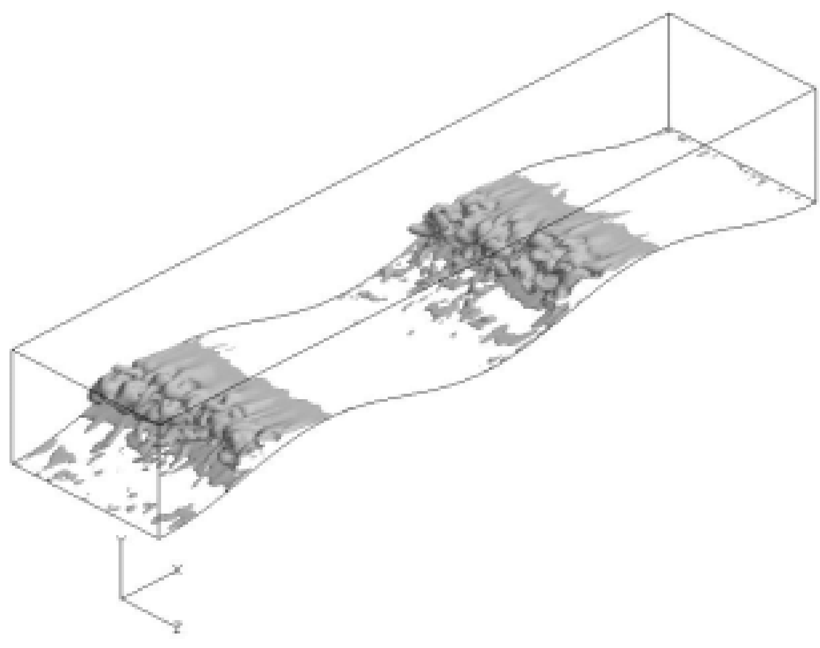
[graph: Total sediment mass in the flow domain as a function of time. Peaks in mass occur during maximum reverse flow and just before maximum forward flow. Streamwise velocity at channel flow is shown for reference.]

The sediment transport patterns mimic the flow and are periodic. A plot of the total sediment mass present in the domain over one wave period is shown together with the velocity at the channel top in Figure 1. This illustrates that there are two main peaks in the total sediment mass: a larger peak during the maximum reverse flow and a smaller peak occurring just before the maximum forward

going flow. These peaks in the sediment mass are due to the increased entrainment of sediment which occurs during maximum flow phases owing to increased shear stress at the bottom. In the time between these peaks, the bottom shear stress is lower, less entrainment results, and sediment settling dominates. Such generic transport patterns during a wave cycle have been observed in the Large Oscillating Water Tunnel at Delft (Katopodi et al. 1994).



(a)



(b)

***Figure 2.** Spanwise vortices form as reverse flow decelerates and cause suspension of sediment into the outer flow. (a) Superimposed spanwise-averaged velocity and sediment contours, on a plane oriented in the streamwise-vertical direction. (b) Iso-contour plot of sediment concentration at the same instant.*

The spatial and temporal distribution of sediment during a wave cycle can be described as follows. As the flow accelerates towards its maximum value in the forward direction, sediment is entrained on the upstream ripple slopes. The forward going flow is not strong enough to cause formation of a recirculation zone, and so the entrained sediment stays close to the bed and is advected along the lee slope, towards the trough, in a thin layer.

As the flow decelerates towards zero velocity, the near-bed sediment settles out as the flow loses its ability to entrain it; any sediment patches aloft are advected along and lose sediment due to settling. As the flow accelerates sufficiently in the reverse direction, it begins to pick sediment up on the upstream ripple slopes once again. The sediment is transported to the lee side of the ripple crests. At maximum reverse velocity a very thin recirculation zone forms, extending over the entire distance from the crest to the trough. As the flow slows down, the recirculation zone grows in height and breaks up into smaller spanwise structures, which are ultimately responsible for suspending sediment high into the flow.

One such structure is visualized in Figure 2a, which shows the spanwise-averaged sediment concentrations superimposed on velocity vectors just after the flow has reversed direction. After this vortex forms, it is lifted off the bottom to an elevation well above the ripple crest height, carrying sediment with it. This mechanism occurs over the entire domain, as can be visualized in Figure 2b, a snapshot of the iso-surface of sediment concentration C = 0.001 (by volume fraction) at the same instant in time as Figure 2a.

IMPACT/APPLICATIONS

The results above demonstrate that Large-Eddy Simulation can provide a detailed physical description of the sediment transport that occurs over ripples and under waves at large Reynolds number. The same code will be used to simulate field experiments; we have recently contacted Prof. Dan Hanes [Univ. of Florida] and Prof. Timothy Stanton [NPS] to obtain data for low to moderate sediment transport events in the nearshore environment.

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